

High Density, High Performance Data Storage via Volume Holography: The Lucent Technologies Hardware Platform

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1.0 Introduction

As illustrated throughout this treatise, it has long been known that volume holography allows multiple pages of data to be stored in the same volume, thereby allowing densities exceeding the diffraction limit for optical storage. The great attraction is the possibility of large storage capacity with the individual high density data pages, (containing $O \sim 10^6$ bits) addressed by changing the angle [1], wavelength [2], or phase code of the reference beams [3], resulting in rapid *parallel* storage and retrieval of digital data. For this reason holography has long been considered as a emerging technology for developing high density, large capacity, fast transfer rate, data storage devices.

Although data storage using volume holography has been proposed since the 1970's it has failed to become a commercial technology because of five key reasons.

- **Material:** There has been no viable material for this technology. Photorefractive media have insufficient sensitivity and dynamic range to be of commercial interest.
- **Methods:** Traditional multiplexing strategies proposed result in complex systems which are difficult to implement. More importantly, geometrical constraints severely limit the maximum density in thin media.
- **Lasers:** Initially proposed laser sources were expensive, complex and extremely unreliable.
- **Detectors:** Fast frame rate, large array detectors that are needed for readout have had relatively poor performance for this application and are generally low yield, high cost devices.
- **Data Input Devices (Spatial Light Modulators, SLM):** Suitable devices developed for the display industry have recently come into existence but their performance characteristics for storage applications have not been adequately tested.

Our research team has made great strides toward solving many of the problems described above. A list of our key technical accomplishments is summarized below.

1) *Using organic, visibly curable, photopolymer based systems, a new write once read many (WORM) material has been developed. This material system can be fabricated into thick (1mm) media, with excellent optical quality ($> \lambda/4$).*

2) *New methods for recording multiplexed holograms have been invented. One innovative technique resolves two of the historic difficulties in implementing holographic storage systems. First, the technique can be implemented with an uncomplicated mechanical geometry where individual holograms are addressed by a simple translation of the media. Secondly, the technique is not dependent upon the Bragg effect, therefore the hologram selectivity is independent of the thickness of the recording media.*

- 3) *A compact, low cost, reliable, high power solid state laser has been developed under contract for storage applications. In addition, commercially available solid-state lasers for the printing and medical markets have advanced significantly.*
- 4) *A newly developed CMOS active pixel detector has been adapted for holographic storage applications. This device, which has lower cost and higher performance than CCD detectors, will allow functionality on a pixel level for data processing or buffering. In addition the device inherently supports high data transfer rates.*
- 5) *We have modified the new Digital Micromirror (DMD) technology developed by Texas Instruments to resolve the input device need. In principle, DMD technology permits > 2000 frame/sec data presentation rates, with 1000:1 bit contrast at 1280x1024 pixels per data page. (Modification of the optical window mounting is required to prevent birefringence.)*
- 6) *Channel encoding, error correction, and tracking issues have been explored to establish feasibility. A demonstration research prototype has been developed capable of full digital data storage and recovery in polymeric media.*

All other technical challenges to holographic storage have been substantially reduced by work described in this treatise. The implication of these developments for deployment of a technology based on volume holography is discussed below. First, in this section we will review the status of our effort detailing the progress made and directions considered.

1.1 Materials

Much of the materials development effort has been discussed earlier in this book in the chapter by Dhar et al [4]. We will simply outline the effort here. Our effort has emphasized photopolymer materials for two dominant reasons. First, the high photosensitivity, high dynamic range, and ease of processing of photopolymer materials for display applications implied that this is a promising material class for adaptation for storage applications [5]. Second, from a system perspective, a WORM (write-once read many times) drive would provide a simple vehicle to explore feasibility and technology development.

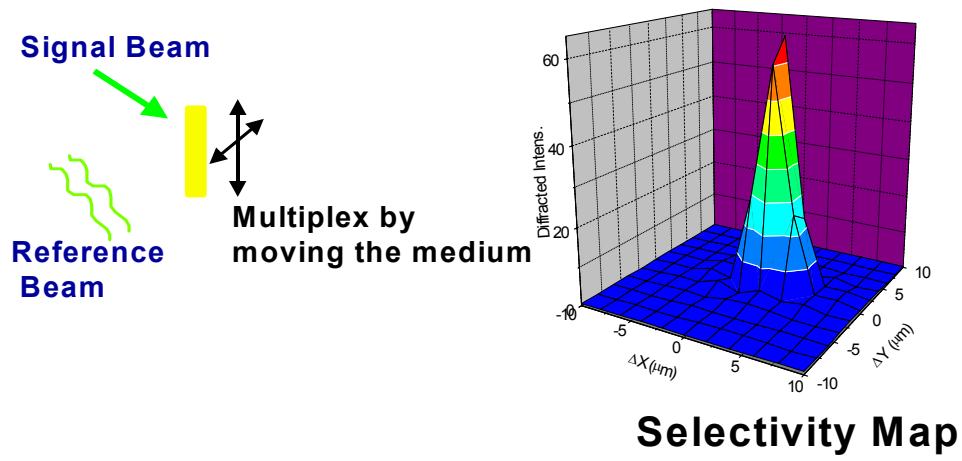
The materials used have been variations on a design strategy in which a crosslinked matrix is formed in-situ, which contains a photoactive species utilized in the recording process. For example, one system consisted of matrix formed by multifunctional acrylate monomers with mono-functional acrylate oligomers that are polymerized during recording [6]. Flat, high optical quality media were fabricated ($< \lambda/4$) using both glass and polycarbonate substrates. The material specifications are also detailed in reference 4. The materials parameters of greatest importance from a system perspective are dynamic range (quantified using the M# and scattering floor) the sensitivity and the optical quality. These key specifications set system limits and the laser power budget for the storage device in development. Details of materials preparation and media design are reviewed in reference [4]. Figure 1 gives an illustration of the optical quality of the media prepared. The media is sandwiched between AR coated glass substrates. The media typically has $< 10^{-6}$ optical scatter and a flatness better than $\lambda/4$ per cm.

Figure 1: Examples of the photopolymer samples used for data storage.

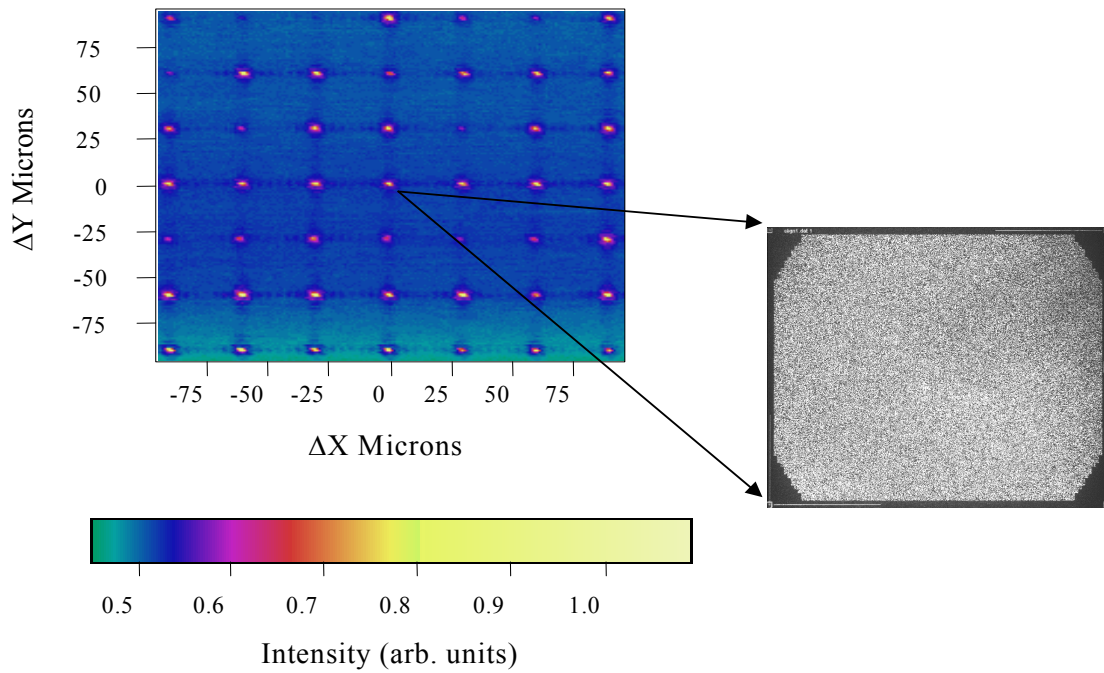


1.2 Multiplexing Methods

The introduction of shift multiplexing, which was conceived at Caltech [7] and reduced to practice at Bell Laboratories [8] lead to a paradigm shift in holographic storage system design concepts. The idea of accessing holograms by simple translation of the media in a manner similar to conventional disk drives greatly simplified device architecture concepts. The primary Bell Laboratories innovation was the development of a novel strategy for multiplexing holograms called Correlation Multiplexing (CM) [9]. In this technique, multiple holograms are stored in an overlapping fashion, accessed by small translations of the medium relative to the incident signal and reference beams. The reference beam is spatially modulated with the hologram position information. This highly complex, bandwidth controlled reference beam relies on the phase, amplitude, and angle differences induced by translating the medium relative to the complex reference for selectivity. The selectivity for a single hologram is *independent* of the thickness of the storage medium. The stored pattern of a single hologram is recovered when the read-out reference beam is centered on the stored image to an accuracy determined by the correlation function of the reference beam, which in practice can be as short as a few microns. This is in contrast to traditional methods employing the Bragg effect, where the selectivity exists in primarily one dimension and grows with material thickness. Figure 2 illustrates the high shift selectivity of CM. Pictured is a single selectivity map (a), (hologram diffraction as a function of media spatial position) and (b) a 7x7 array of stored holograms in a polymeric media. The diffracted intensity maximums are on 30 μm centers with a full width at half maximum of $\sim 3\text{ m}$ (each representing a stored data page). It is important to note that CM is unique in that the selectivity obtained is *independent of both material thickness and signal bandwidth, and has high SNR*. The selectivity of few other multiplexing methods such as employing fractal sampling grids [10], peristrophic multiplexing [11], or aperture multiplexing [8], are independent of material thickness, but depend on the signal beam bandwidth. Thus the more information each hologram contains, the lower the selectivity. Using our novel techniques, higher densities can be stored thin media. Using CM, storage densities in excess of 350 channel bits/ μm^2 have been demonstrated in 4mm Fe doped LiNbO₃ at a capacity of the order of 4 Gbits, (16,000 holograms).



(a)



(b)

Figure 2a & b: a) Selectivity map for a single CM recorded hologram. b) An array of holograms; Scan of hologram diffraction efficiency as a function spatial position. At each maximum a greater than 480Kbit data page is stored, as shown. The sample was a 250 μm polymer film.

1.3 Components

During the last five years several components essential to the development of any viable holographic storage system have been developed. The three key devices are low cost, highly coherent laser sources, a high speed, high throughput, input device, and finally a high speed, low cost, output device. Figure 2 shows a block diagram of necessary components. (Here we have omitted mechanical actuators, concentrating on components unique to holographic applications.) While the figure shows a general configuration read-write device, only the components inside the dotted box are required for a read only memory (ROM).

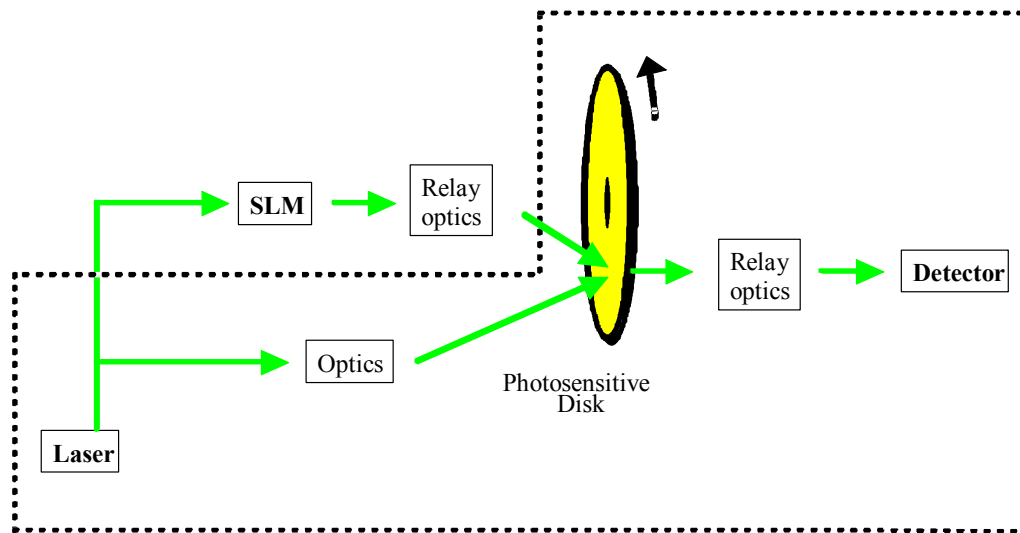


Figure 2: Block diagram of a holographic storage system. The key components are in bold.

The laser source required must be low cost with moderate power (100-200mW), have a long coherence length (0.1– 1m), and a TEM₀₀ beam profile. Diode pumped solid-state sources allow for flexibility in system design. We utilize doubled Nd:Yag sources (many of these devices are available commercially). A 100mW, Coherent Radiation model Compass 315 is used in the demonstration system described below. Although technically, lasers of adequate quality have reached maturity, the cost of laser devices is still an issue. Low cost lasers such as those used in compact disks players, though inexpensive, do not have the required coherence properties. Currently the sources of choice cost in the \$2K-20K range and although prices are dropping, the lack of a high volume application for these devices may limit the rate of this cost decline. One example of a possible source is a monolithic microchip laser [12], which could serve the holographic storage application well. These diode pumped solid state devices naturally lase in a single longitudinal TEM₀₀ induced by the dimensions of the microresonator. The small volume of active material used may allow high volume production of these devices. A 100mW prototype device was developed under contract to demonstrate technical feasibility.

The input device encodes the digital data onto the object beam. This of course needs to be done at a fast frame rate (> 100 frames/sec) with as high an efficiency as possible to have minimal effect on the laser power budget. Liquid crystal devices are commonly suggested for this application but they have insufficient throughput and frame rate. More viable choices are the Texas Instruments Digital Micromirror

Device, (DMD) or ferroelectric liquid crystal displays, (Displaytech). We have used primarily the DMD as our input device [13]. This device, designed for projection television applications, has 2kHz frame rates and high throughput ($< 50\%$ typical). In the demonstration device, the modulator is a 848×600 array of $16\mu\text{m}$ mirrors on $17\mu\text{m}$ cantelevered centers. The individually addressable mirrors steer the input beam either down or out of the optical path, yielding binary “on” and “off” states. Commercial devices exhibited extensive birefringence, introduced due to stress in the optical window (figure 3a). Though not important for projection applications, birefringence could be fatal in a holographic device. By modifying how the optical windows were mounted onto the device we eliminated this problem, resulting in an extremely low birefringence device (b). The DMD also has very high contrast. For the first 2.5 Fourier orders of reflected light, the device used had a efficiency of 53% and a 800:1 contrast for digital data. Figure 4 shows a magnified single bit chessboard pattern illustrating the high contrast of the device.

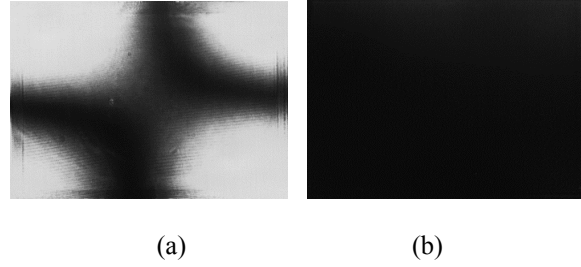


Figure: 3 Birefringence. (a) Original window (b) Modified window;
both measured interferometrically

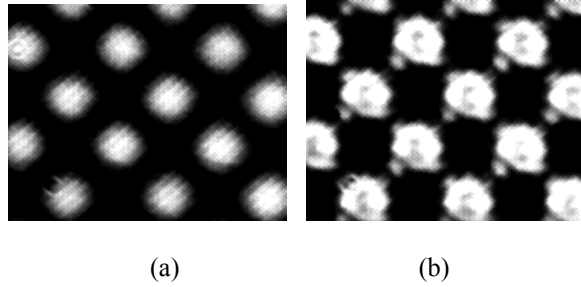


Figure: 4 ~25 DMD Pixels. (a) Low-Pass, 32% eff. (b) 2.5-Pass, 53 % eff. Contrast ~ 800.

For the output device speed and cost are crucial. Although high-speed CCD detectors have been developed, the prospect for *low cost*, high performance devices is questionable. CMOS Active Pixel Sensors (APS) are a better solution. These devices, made in a conventional silicon process, have a high probability for high yield, low cost manufacturing. In addition, these devices may allow integration of complex processing functions on the detector. CMOS is an inherently fast, (nsec switching response), low power technology allowing great device versatility. APSs typically require only 1% of the power needed to operate comparable CCDs. Generally an APS can operate uncooled at room temperature with resolution in excess of ten bits at video-rate capture. Furthermore, packaging costs for CCDs are approximately ten times those for APSs because the heat generated by CCDs. Finally, because CMOS cameras are fabricated in standard CMOS integrated circuit fabrication lines, their production costs are well below those of CCDs, which rely on highly specialized fabrication processes. The APS camera used in our demonstration system was co-designed and fabricated by Photobit, LLC, (Pasadena, CA). The detector was designed to match the DMD device mentioned above allowing 1-1 pixel matching. We have also demonstrated oversampled data recovery.

1.4 Holographic Demonstration System.

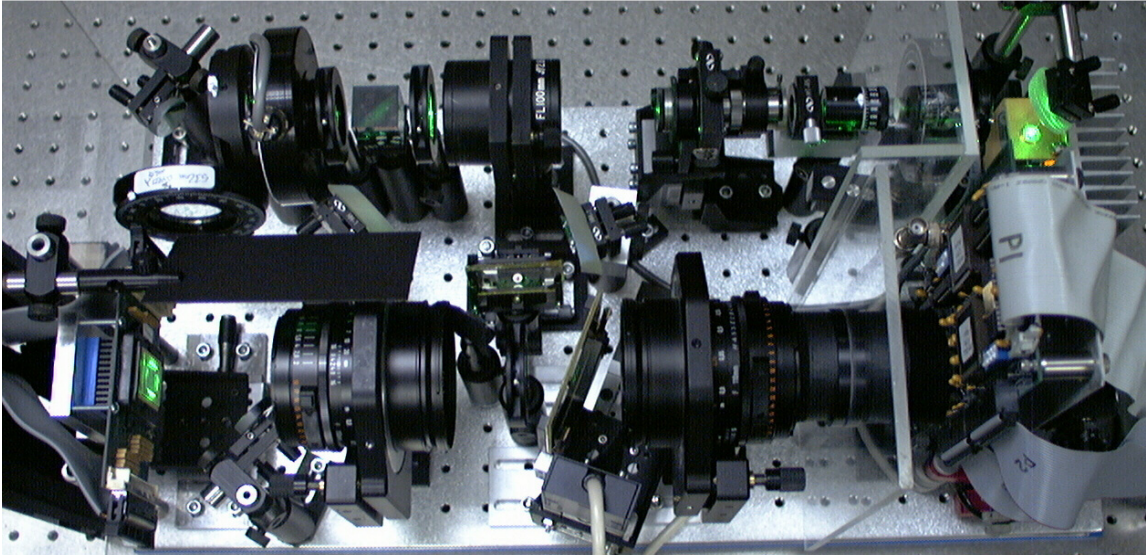


Figure 5: Demonstration System; this 1x2ft device is fully functional and allows for digital data storage and recovery from a polymeric media.

Our team has developed a demonstration storage system based on CM. Taking advantage of a closely coupled materials and system development effort, a research prototype system capable of automated storage and recovery of pixel matched holograms has been constructed [14]. The system is shown in figure 5. The $\sim 480\text{Kb}/\text{page}$ system is the first of its kind using a photopolymer as media. Figure 6 shows an example of a recovered data page, the edge markings are used for alignment and feedback. Raw bit error rates of the order of 10^{-5} have been observed for recorded data pages recovered in $280\mu\text{m}$ polymer films. Error correction codes have allowed error free recovery of a wide variety of stored data at high density. Note, all optical components (lenses, beamsplitters, etc) are standard camera optics or “off the shelf components”; no custom optics of any kind have been used.

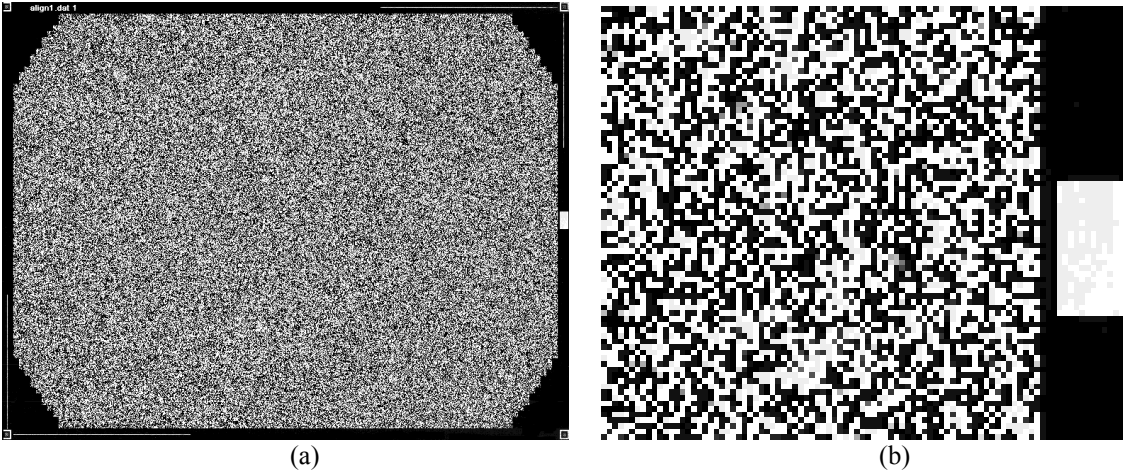


Figure 6: Typical recalled data page (800 x 600 pixels) from our demonstration system using a DMD SLM and CMOS APS camera. (a) Whole data page. (b) Zoom-in on (Data stored in a $280\mu\text{m}$ thick layer of photopolymer.)

Significant progress in characterizing this unique data channel has been achieved, leading to data page normalization and the application of new, powerful, and more compatible error correction codes. Use of these codes will dramatically reduce system overhead and increase robustness for the next generation device. Currently, we have written ~ 4000 holograms, ($\sim 1\text{ Gbit}$ of data), at a user density of $\sim 45\text{bits}/\mu\text{m}^2$, corresponding to an $\sim 50\text{GB}$ of user capacity in a 5-1/4 inch disk. A plot illustrating the progression of measured density in our apparatus is given in figure 7. The maximum density achieved has been limited by

the material's dynamic range. We now have higher dynamic range (4x) formulations in hand that should support *150 Gbytes of USER* capacity in the same format greater than 30MB/sec transfer rates.

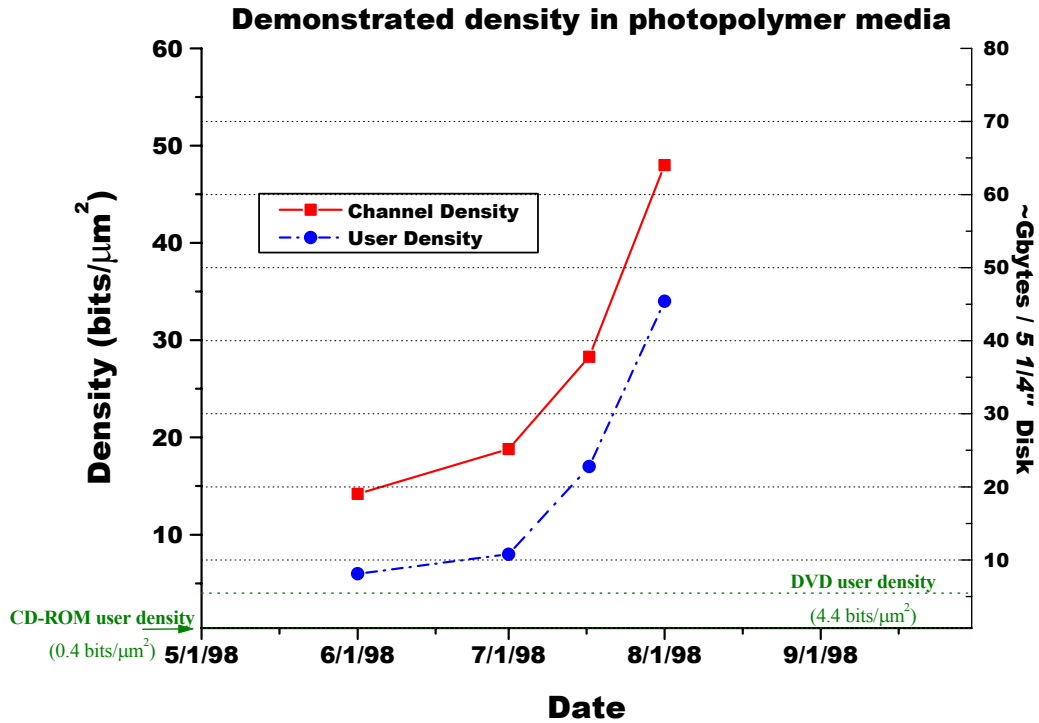


Figure 7: A plot of the density progress made with our hardware platform, measurements are made using 750μm media.

1.5 Summary

The development of this material class and the evolution of the component technologies have moved the holographic storage closer to viability. The technical feasibility of a high performance WORM or ROM device has been established. The risks associated with drive engineering are at this point comparable to the industry standard. The most critical risks are still material related ; in particular, archival lifetime, shelf life and manufacturability. Preliminary research on these issues for our materials has been promising, but work is on-going. Finally, the key determining factors in this technology's success will be drive cost and finding the right market for a high performance WORM system.

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